# Predicting Surgical Outcomes in Patients With Recurrent Patellar Dislocations

Dario De Caro,* MS, Nathan L. Grimm,† MD, J. Lee Pace,‡§ MD, John A. Curran,* BS, and Clare K. Fitzpatrick,*‖ PhD
*Investigation performed at Boise State University, Boise, Idaho, USA*

**Background:** A lateral dislocation of the patella is a common injury in adolescents and young adults that is largely caused by underlying anatomic risk factors. Surgically managed patients have a significantly lower risk of recurrent dislocations. However, determining the optimal surgical treatment remains a challenge, with patients sometimes undergoing multiple surgical procedures before achieving successful stabilization.

**Purpose:** To computationally evaluate patients who have undergone multiple surgical procedures to treat recurrent lateral patellar dislocations and predict their clinical outcomes.

**Study Design:** Controlled laboratory study.

**Methods:** Our cohort consisted of 16 patients with trochlear dysplasia and recurrent lateral patellar dislocations. We used magnetic resonance imaging to create 3-dimensional patient-specific finite element models of the knee joint and evaluated patellofemoral stability before and after surgery. We applied these models to computationally predict the clinical outcome of each surgical procedure. We simulated a knee extension activity coupled with external tibial torsion to assess patellofemoral stability. We also included a healthy control group of 12 participants in the computational evaluation. Finally, we developed and trained a logistic regression model based on anatomic risk factors and applied this model to classify whether patients had a likelihood of a dislocation to efficiently differentiate between surgical outcomes.

**Results:** Of 12 control, 12 preoperative, and 9 postoperative scans, the finite element model correctly predicted 29 of 33 surgical outcomes (87.9% accuracy). Postoperative simulations predicted patellofemoral stability metrics similar to those of the control group. Specifically, patients after trochleoplasty were associated with increased constraint force on the patellar lateral facet and lower involvement of the medial patellofemoral ligament. The logistic regression model demonstrated 81.8% accuracy in classification.

**Conclusion:** Preliminary results are promising, but an improvement of the model and a larger clinical dataset are necessary to increase accuracy and comprehensively validate model performance.

**Clinical Relevance:** The aim of this study was to provide surgeons with a useful computational tool that can predict the likelihood of a patellar dislocation and differentiate, before a clinical intervention, between successful versus unsuccessful surgery to determine the optimal treatment pathway for individual patients.

**Keywords:** patellar dislocation; finite element modeling; surgery; trochlear dysplasia; patellofemoral mechanics

A lateral dislocation of the patella is a common injury in adolescents and young adults.[4] A patellar dislocation occurs when the patella disengages completely from the trochlear groove. When dislocations are isolated and the existing patellar mechanics and anatomy can accommodate the rehabilitation process, nonsurgical management is preferred.[2] However, patients who are ultimately managed surgically have a significantly lower risk of recurrent dislocations at 2 to 5 years' follow-up,[21] suggesting that pathoanatomy plays a dominant role in patellar instability. Research has shown that recurrent patellar instability is associated with anatomic abnormalities, including trochlear dysplasia, patella alta, femoral anteversion, genu valgum, and increased tibial tubercle–trochlear groove (TT-TG) distance. Recent work has also shown a strong association between an increased TT-TG distance and external tibial rotation.[3,5,11,23] Of all the anatomic risk factors, trochlear dysplasia is the most common and has been found radiographically in up to 90% of

The Orthopaedic Journal of Sports Medicine, 13(3), 23259671251324527
DOI: 10.1177/23259671251324527

patients who undergo a surgical intervention for recurrent patellar instability.[18]

Common surgical options in the United States are medial patellofemoral ligament (MPFL) reconstruction (MPFLR) and tibial tubercle osteotomy.[12] In Europe, trochleoplasty is considered a first-line treatment approach for patients with recurrent patellar instability and high-grade trochlear dysplasia.[24] However, because no evidence-based surgical algorithms exist, determining the optimal surgical treatment for patients with patellar instability and trochlear dysplasia remains a challenge, with patients sometimes undergoing multiple surgical procedures before achieving successful stabilization.

Computational models have been used to associate patellar tracking with anatomic parameters for patients with recurrent patellar instability. Knee models are usually created using computed tomography or magnetic resonance imaging (MRI) and used to perform dynamic simulations. Elias et al[8] demonstrated that, during an extension activity, patellar tracking is related to both trochlear dysplasia and the tibial tuberosity position, but the relationship changes with the flexion angle. The use of patient-specific computational models also allows us to quantitatively evaluate the effect of different surgical options on patellofemoral joint stability metrics relative to the underlying anatomy. Previous computational studies that have simulated procedures to treat patellar dislocations indicated that patient-specific interventions that correct underlying anatomic abnormalities are the only surgical options to restore joint stability to the statistical equivalent of a healthy control group.[1] Other studies have shown that trochleoplasty significantly decreased lateral patellar tracking, particularly at low knee flexion angles, decreased the contact area, and increased maximum contact pressure at multiple flexion angles, thus reducing the risk of patellar dislocations.[7]

While these simulations allow us to quantify stability metrics and develop relative ranking across a variety of procedures, it is not obvious if the differences identified between simulations are clinically relevant to patient outcomes and surgical success. Notably, previous simulations have assessed patellofemoral stability in the absence of clinical data to determine whether "virtual" surgery would have a real-world impact on a patient's clinical outcome. Additionally, these studies typically applied a generic or stylized loading condition rather than reproduce more complex loading conditions of daily living that place a patient at risk of patellar dislocations during an in vivo activity.[7,8]

The objective of this study was to computationally evaluate patients with patellar instability and trochlear dysplasia who have undergone surgical procedures to treat recurrent lateral patellar dislocations and to evaluate how well these models can predict their clinical outcomes. We used patient-specific imaging to create 3-dimensional (3D) finite element (FE) models of the knee joint and evaluated patellofemoral stability at multiple time points before and after surgery. We evaluated whether our computational approach can accurately predict the success or failure of each surgical procedure. We also developed and applied a logistic regression model to determine if we can accurately predict surgical success from anatomic risk factors alone.

## METHODS

### Patients and Data Collection

We retrospectively obtained MRI scans of the knee joint from 28 participants: 16 patients with recurrent lateral patellar dislocations plus 12 healthy control participants. Patients were extracted from a larger patient cohort that underwent a surgical procedure for recurrent patellar instability due to high-grade trochlear dysplasia between September 2017 and July 2021. High-grade trochlear dysplasia was defined as proximal trochlear morphology that was either flat or convex as opposed to a normal concavity. All patients were aged between 12 and 19 years at the time of surgery. Inclusion criteria for this study were patients who underwent trochleoplasty and/or MPFLR and had a preoperative and/or postoperative MRI scan, with those undergoing trochleoplasty requiring both preoperative and postoperative scans to quantify morphological changes to the trochlea. Specifically, we had (1) only preoperative scans for 7 patients, (2) only postoperative scans for 4 patients after undergoing MPFLR, and (3) both preoperative and postoperative scans for 5 patients after undergoing both MPFLR and sulcus-deepening trochleoplasty. Overall, we obtained a total of 33 scans that we used to build patient-specific models: 12 preoperative, 9 postoperative (4 after MPFLR, 5 after MPFLR + trochleoplasty), and 12 control (Table 1).

At a minimum 2-year follow-up, there were no reported cases of patellar instability in the patients since surgery.

||Address correspondence to Clare K. Fitzpatrick, PhD, Department of Mechanical and Biomedical Engineering, Boise State University, 1910 West University Drive, MS-2085, Boise, ID 83725, USA (email: clarefitzpatrick@boisestate.edu).

*Department of Mechanical and Biomedical Engineering, Boise State University, Boise, Idaho, USA.

†Idaho Sports Medicine Institute, Boise, Idaho, USA.

‡Connecticut Children's Medical Center, Farmington, Connecticut, USA.

§Children's Health Andrews Institute, Plano, Texas, USA.

Final revision submitted September 13, 2024; accepted November 6, 2024.

One or more of the authors has declared the following potential conflict of interest or source of funding: N.L.G. has received hospitality payments from Arthrex, Steelhead Surgical, Smith & Nephew, and Stryker and education payments from Steelhead Surgical. J.L.P. has received nonconsulting fees from Arthrex, consulting fees from Arthrex and JRF Ortho, and education payments from Pylant Medical and Kairos Surgical. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was waived by Boise State University (130-MED16-010).

TABLE 1
Characteristics of Models[a]

| | Preoperative (n = 12) | Postoperative (n = 9) | Control (n = 12) | Total (n = 33) |
|---|---|---|---|---|
| Sex, male/female, n | 6/6 | 2/7 | 6/6 | 14/19 |
| Age, mean ± SD, y | 15.0 ± 2.5 | 15.5 ± 2.3 | 21.7 ± 2.0 | 17.57 ± 3.87 |

[a]MPFLR, medial patellofemoral ligament reconstruction.

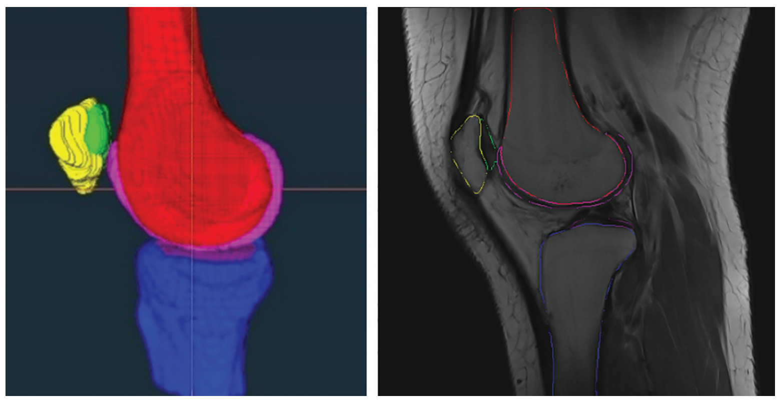

**Figure 1.** Segmentation of bone and cartilage geometries from patient-specific magnetic resonance imaging scans.

Control participant data were collected as part of a separate study. None in the control group had a prior knee injury. All scans were obtained as part of standard patient care and were anonymized before inclusion in this study; accordingly, the study protocol received an exemption from our university's institutional review board.

## Model Development

We constructed patient-specific models to evaluate trochlear morphology, patellar height, and TT-TG distance. We imported and segmented MRI scans using commercially available reconstruction software (Amira; Thermo Fisher Scientific) to create a patient-specific 3D model of each knee joint (Figure 1). Each model included femoral, tibial, and patellar bone and cartilage geometries. We scaled and aligned generic quadriceps muscles and tendons, patellar tendons, and MPFLs to match patient-specific bone and cartilage geometries (Figure 2). We aligned models from different time points with one another using an iterative closest point algorithm. We created local tibiofemoral and patellofemoral joint coordinate systems to define 6 degrees of freedom translational and rotational axes according to Grood and Suntay.[13]

We calculated 5 geometric factors from the reconstructed 3D model: patellar height, TT-TG distance, trochlear dysplasia, lateral trochlear inclination, and bisect offset index.

- Patellar height was defined as the Insall-Salvati ratio, which is the ratio of the patellar tendon length to the superior-inferior length of the patella.

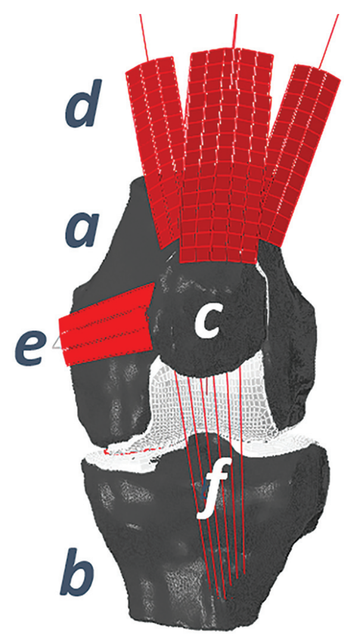


**Figure 2.** Three-dimensional finite element model of a patient-specific knee joint reconstructed from magnetic resonance imaging scans, including the (A) femur, (B) tibia, (C) patella, (D) quadriceps tendon, (E) medial patellofemoral ligament (MPFL), and (F) patellar tendon.

- Trochlear dysplasia was defined by the sulcus angle, which is the angle subtended between the most proximal aspect of the medial and lateral trochlear facets. A sulcus angle >145° was defined as a dysplastic trochlea.

- Lateral trochlear inclination was the angle subtended along the most proximal aspect of lateral trochlear cartilage and the tangent of the posterior femoral condyle. A lateral trochlear inclination ≤11° has been shown to have a specificity of 0.95 in discriminating between patients with and without symptomatic trochlear dysplasia.[6]
- TT-TG distance was measured as the medial-lateral distance (parallel to the posterior condylar line) from the anterior point of the tibial tuberosity to the deepest point of the trochlear groove.
- Bisect offset index was defined as the proportion of the patella lying lateral to the midline of the trochlea as a percentage of the whole patellar width.[16]

### FE Model

We imported bone geometry into HyperMesh (Altair) and meshed the surfaces as rigid triangular elements with an approximately 1-mm edge length. We represented cartilage as 8-noded hexahedral elements using publicly available automated hexahedral meshing software implemented in MATLAB (MathWorks).[20] We modeled the patellar tendon as 6 nonlinear springs and the quadriceps tendon and MPFL as 2-dimensional membranes (quadrilateral elements) with embedded fiber-reinforced springs.

We created the FE model in Abaqus/Explicit (SIMULIA) and performed a dynamic simulation. We applied an initial force of 100 N to the quadriceps, distributed with a ratio of 20:20:35:25, respectively, across the rectus femoris, vastus intermedius, vastus lateralis, and vastus medialis.[9] We applied an 8-N force to the MPFL to create a pretensioned state at full extension while allowing for a slack MPFL later in flexion.[1,9] To evaluate the effect of MPFL force on our results, we performed a sensitivity analysis of the MPFL pretensioning force, increasing and decreasing the initial value of 8 N by 50% and evaluating differences in classification performance. We applied a compressive force of 50 N across the tibiofemoral joint to ensure tibiofemoral articular contact throughout the simulation. While loaded, we flexed the knee to 90°. Starting from this flexed position, we simulated a weighted knee extension activity. Specifically, we used experimental data to kinematically apply tibiofemoral flexion-extension, internal-external, medial-lateral, and anterior-posterior motions throughout the activity.[14] Adduction-abduction rotation and superior-inferior displacement were kinematically unconstrained, with their motions determined by articular contact between the femur and tibia. We used a pressure-overclosure relationship of 3.2 MPa/mm to define cartilage contact mechanics at the tibiofemoral articular surface.[10] The applied quadriceps force ranged from 100 to 750 N throughout the activity. We applied 30° of external tibial rotation to evaluate patellofemoral joint stability under a challenging loading condition.[22]

### Postprocessing

For each simulation, we evaluated a series of patellofemoral joint stability metrics. This analysis focused on the last 40° of extension in which anatomic resistance to a dislocation is reduced and soft tissue constraint necessary to maintain a stable joint is increased.[9] Specifically, the simulation reported total force on the MPFL and contact force on the patellar articular surface throughout the activity. As there is not an established method to define exactly when a dislocation occurs within a computational simulation, we defined the patella as dislocated if the total force on patellar cartilage switched from a medial to lateral direction, indicating that it disengaged completely from the trochlear groove. However, other metrics could have been used (eg, the relative medial-lateral position of the patella with respect to the lateral facet of the trochlear groove).

Subsequently, we simulated "virtual" trochleoplasty in the postoperative group to increase the depth of the femoral sulcus angle to 140° to evaluate sensitivity to change in sulcus depth as a result of the trochleoplasty procedure. We implemented this procedure using a method described in detail in our prior work.[1] In brief, we used radial basis functions to simulate sulcus-deepening trochleoplasty. There were 3 landmark points used to calculate the sulcus angle with the knee flexed sequentially to 0°, 30°, 60°, and 90°. Radial basis function points were morphed to generate a sulcus angle of 140° at full extension, which blended smoothly with the native anatomy at the most posterior point of the groove.

We performed 5 one-way analyses of variance (one for each anatomic factor) between the control group, preoperative group, and postoperative group to examine the null hypothesis that no significant differences exist in the mean value of each factor among groups. Statistical significance was set to .05. We performed tests for normality and the equality of variance in addition to post hoc Bonferroni tests to establish which groups showed significant difference and to account for correlation among factors. We performed a power analysis to determine the statistical power of the test with the current dataset size.

### Logistic Regression Classification Model

In addition to the FE simulations described above, we evaluated the ability of a simple logistic regression model to predict the likelihood of a dislocation based only on anatomic risk factors and to determine a binary classification (dislocation or no dislocation). Previous studies have shown that multivariable models can identify patients who are at a high risk for recurrent dislocations.[17] We used backward elimination as a predictor selection technique and the "leave-one-out" method for cross-validation because of the small sample size. We quantified model performance using an accuracy classification score.

## RESULTS

### FE Model

The FE model was able to correctly predict 29 of 33 surgical outcomes (87.9% accuracy). Misclassifications occurred

TABLE 2
Rate of Correct Classifications by MPFL Pretensioning Force[a]

| | Preoperative (n = 12) | Postoperative (n = 9) | Control (n = 12) | Total (n = 33) |
|---|---|---|---|---|
| 8 N | 9 (75) | 8 (89) | 12 (100) | 29 (88) |
| 4 N | 9 (75) | 8 (89) | 12 (100) | 29 (88) |
| 12 N | 8 (67) | 8 (89) | 12 (100) | 28 (85) |

[a]Data are shown as n (%). MPFL, medial patellofemoral ligament.

TABLE 3
Values of Anatomic Factors[a]

| | Preoperative | Postoperative | Control |
|---|---|---|---|
| Insall-Salvati ratio | 1.6 ± 0.3 | 1.4 ± 0.3 | 1.4 ± 0.2 |
| Sulcus angle, deg | 160 ± 11 | 145 ± 10 | 138 ± 8 |
| TT-TG distance, mm | 14.3 ± 5.3 | 12.3 ± 4.9 | 7.7 ± 3.0 |
| Bisect offset index | 0.87 ± 0.14 | 0.67 ± 0.15 | 0.58 ± 0.07 |
| Lateral trochlear inclination, deg | 10.4 ± 4.5 | 15.8 ± 4.5 | 18.5 ± 4.5 |

[a]Data are shown as mean ± SD. TT-TG, tibial tubercle–trochlear groove.

TABLE 4
*P* Values for Anatomic Factors[a]

| | Preoperative vs Postoperative | Preoperative vs Control | Postoperative vs Control |
|---|---|---|---|
| Insall-Salvati ratio | .212 | .091 | .856 |
| Sulcus angle | **.004** | **.001** | .108 |
| TT-TG distance | .400 | **.001** | **.015** |
| Bisect offset index | **.006** | **.001** | .074 |
| Lateral trochlear inclination | **.015** | **.001** | .187 |

[a]Significant values (<.05) are shown in bold. TT-TG, tibial tubercle–trochlear groove.

in 3 preoperative simulations in which the model was not able to predict a dislocation (3 false negatives) and in 1 postoperative simulation in which the model predicted a false dislocation (1 false positive). By decreasing the MPFL initial force by 50% to 4 N, classification performance was not affected in any of the groups. Increasing the force by 50% to 12 N resulted in misclassifications in 4 preoperative simulations and 1 postoperative simulation (4 false negatives and 1 false positive) (Table 2).

When comparing the results of analyses of variance and post hoc Bonferroni tests among the preoperative, postoperative, and control groups, the Insall-Salvati ratio was the only factor to show no significant difference between groups. For all the other factors, the control group was significantly different from the preoperative group but not from the postoperative group (Tables 3 and 4), suggesting that surgery was able to restore the anatomic condition close to normal.

When comparing MPFL force and contact force on patellar cartilage, postoperative simulations showed results trending toward the control group (Figure 3). A deeper sulcus angle was associated with increased constraint force on the patellar lateral facet and lower involvement of the MPFL, mostly close to full extension. The same analysis was applied to the virtual trochleoplasty simulations (Figure 4). Virtual surgery showed an even higher trochlear constraint force, mostly between 20° and 40° of flexion, while no effect was shown for the MPFL total force. The control group still performed best most likely because of better mean values for the other anatomic factors.

## Logistic Regression Classification Model

Backward elimination provided a logistic regression model with only 2 significant predictors ($P < .05$): lateral trochlear inclination and bisect offset index. Statistical information of the model is shown in Table 5.

After applying the "leave-one-out" method of cross-validation, we used the accuracy classification score to describe the performance of the model to classify dislocations and nondislocations. The accuracy was 81.8% in classification. In general, the logistic regression model was a worse predictor of dislocation events than the FE simulations.

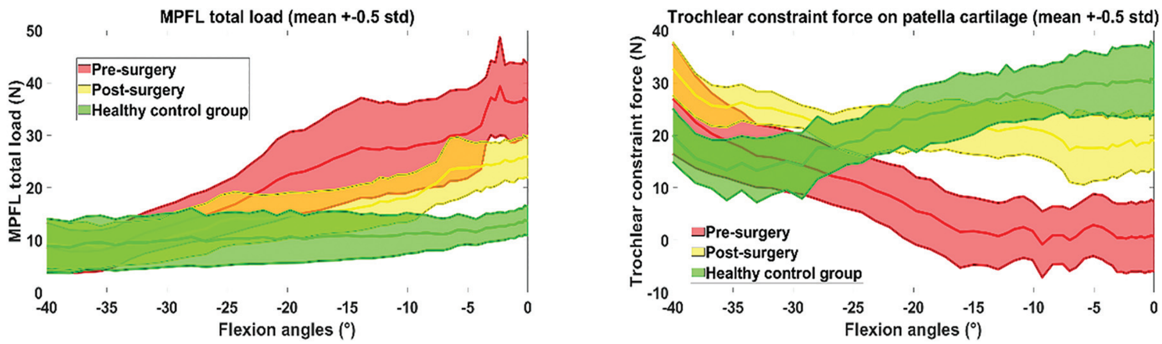


**Figure 3.** Mean total medial patellofemoral ligament (MPFL) constraint force (left) and contact trochlear constraint force on patellar cartilage (right) at different flexion angles for different groups.

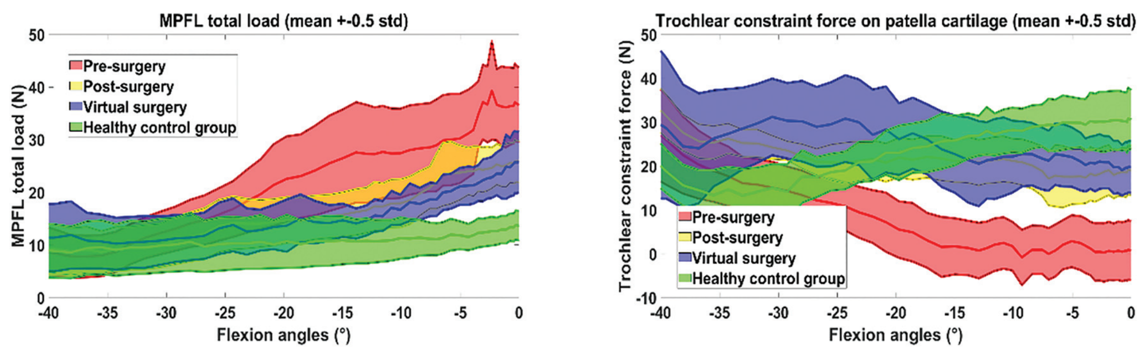


**Figure 4.** Effect of virtual trochleoplasty on patellofemoral joint stability metrics.

TABLE 5
Statistical Values for Predictors in Logistic Regression Model

| | Coefficient | Standard Error | *Z* | *P* | 95% CI |
|---|---|---|---|---|---|
| Bisect offset index | 6.82 | 2.54 | 2.69 | .007 | 1.85 to 11.79 |
| Lateral trochlear inclination | –0.41 | 0.14 | 2.86 | .004 | –0.69 to −0.13 |

## DISCUSSION

A lateral patellar dislocation is a common injury, and there is no general consensus on the optimal treatment strategy on a patient-specific basis. The overall aim of this study was to develop a useful computational tool that can predict the likelihood of a patellar dislocation and differentiate, before a clinical intervention, between successful versus unsuccessful prospective surgery. This may assist the surgeon in determining the optimal treatment pathway for individual patients. We evaluated 2 different approaches: FE and logistic regression models. Overall, FE and logistic regression models were able to predict a patellar dislocation with an accuracy of 87.9% and 81.8%, respectively.

The FE model was able to provide additional information besides the dislocation risk. Specifically, total constraint force on the MPFL and total contact force on patellar cartilage were useful metrics to establish the mechanism of a dislocation and the potential risk of MPFL ruptures. In addition, the overall accuracy of the FE model was higher. However, this method is more prohibitive as a surgical guidance tool; it requires technical expertise to develop and run these simulations and post-process the results as well as computational resources (dedicated software and simulation time). Training the logistic regression model requires only the anatomic factors for each patient, and it runs almost instantaneously. In this study, we measured all the anatomic factors used in the logistic regression model from the reconstructed 3D models. In future work, we plan on performing the same analysis with measurements directly from the MRI scans, which would eliminate the need to reconstruct these scans. It may be helpful to establish the accuracy and repeatability of a direct MRI measurement method and

TABLE 6
Power Analysis Based on Anatomic Factors[a]

| | Effect Size | Statistical Power, % |
|---|---|---|
| Insall-Salvati ratio | 0.34 | 14.3 |
| Sulcus angle | 1.15 | 85.4 |
| TT-TG distance | 0.75 | 48.2 |
| Bisect offset index | 1.21 | 89.0 |
| Lateral trochlear inclination | 0.89 | 63.9 |

[a]TT-TG, tibial tubercle–trochlear groove.

possibly define correction factors between the 2 different approaches.

Previous computational studies have mostly focused on associating anatomic factors with patellar tracking.[19,25] Our computational framework applied a previously developed FE model of patellar dislocations to patient data with known clinical outcomes, facilitating the quantification of model performance against real-world data. The logistic regression model represents a new and potentially useful alternative, particularly efficient in terms of computational cost. Recent studies have also applied multivariate statistical models to predict the risk of patellar dislocations based on anatomic factors.[3,15,17,26] In addition to the anatomic factors already used in this study, other parameters considered were skeletal immaturity, age, history of a contralateral patellar dislocation, and lateral patellar tilt. To our knowledge, this study is one of the first studies that applied both a computational model and a data-driven model on the same dataset to predict the risk of patellar dislocations, classify surgical outcomes, and compare classification performance.

While these preliminary results are promising, there are a number of limitations associated with this work. First, we need to increase the sample size to increase the statistical power of our study; with the current dataset, only sulcus angle and bisect offset index reached statistical power >80% (Table 6). Unfortunately, preoperative and postoperative MRI scans are not often part of standard patient care, making it difficult to build a large-scale patient database. There are also additional improvements and extensions that we can make to our models; only MPFLR and trochleoplasty were considered as surgical options, as they were the only surgical procedures performed on the patients available through the current dataset. To expand the scope of this analysis to a more comprehensive assessment of potential surgical options, patients who have undergone tibial tubercle osteotomy (which would likely impact the Insall-Salvati ratio and TT-TG distance) should also be included.

There are also some simplifications and limitations associated with the FE model. The patellar tendon is the only soft tissue structure for which we implemented an automatic alignment process. Specifically, we used the most prominent point on the tibial tubercle and lowest point on the patella as the attachment sites of the patellar tendon. We manually aligned the MPFL and quadriceps tendon based on bony landmarks. For this reason, the selection of attachment sites is subject to some interuser variability as well as increasing the total time for model preparation. Additionally, MRI scans were localized to the knee; thus, patient-specific quadriceps attachment sites at the hip were not available. In the absence of patient-specific data, it may be possible to implement an automated method (similar to that used for the patellar tendon) to ensure consistency among patients. In addition, we simulated only 1 loading condition. Although this better represents a dislocation-inducing activity than most previous models, external tibial torsion is not the only mechanism that can lead to a patellar dislocation. Also, both the loading and kinematics profiles were not patient specific, as these data are not collected as part of standard preoperative practice. Model predictions would likely improve if all inputs were patient specific, but currently, that would be difficult or infeasible to implement outside of a research setting.

Lastly, regarding classification, only logistic regression was used as a predictor model. There is potential that other classification methods may improve the results presented here. In addition, although the 5 anatomic parameters included in this model are considered the main risk factors for a patellar dislocation, we did not evaluate a more comprehensive set of parameters that could be added to train the model and that may improve model performance. However, despite these limitations, results are promising, reinforcing the importance and potential impact of both computational and data-driven models in the decision-making process for clinicians and setting the stage for future exploration and research in this field.

## ORCID iD

Clare K. Fitzpatrick https://orcid.org/0000-0002-8200-9353

## REFERENCES

1. Alvarez O, Steensen RN, Rullkoetter PJ, Fitzpatrick CK. Computational approach to correcting joint instability in patients with recurrent patellar dislocation. *J Orthop Res*. 2020;38(4):768-776.
2. Andrish J. The management of recurrent patellar dislocation. *Orthop Clin North Am*. 2008;39(3):313-327, vi.
3. Arendt EA, Askenberger M, Agel J, Tompkins MA. Risk of redislocation after primary patellar dislocation: a clinical prediction model based on magnetic resonance imaging variables. *Am J Sports Med*. 2018;46(14):3385-3390.
4. Arendt EA, Fithian DC, Cohen E. Current concepts of lateral patella dislocation. *Clin Sports Med*. 2002;21(3):499-519.
5. Balcarek P, Oberthur S, Hopfensitz S, et al. Which patellae are likely to redislocate? *Knee Surg Sports Traumatol Arthrosc*. 2014;22(10): 2308-2314.
6. Carrillon Y, Abidi H, Dejour D, Fantino O, Moyen B, Tran-Minh VA. Patellar instability: assessment on MR images by measuring the lateral trochlear inclination. Initial experience. *Radiology*. 2000;216(2):582-585.
7. Elias JJ, Rezvanifar SC, Koh JL. Groove-deepening trochleoplasty reduces lateral patellar maltracking and increases patellofemoral contact pressures: dynamic simulation. *J Orthop Res*. 2022;40(7): 1529-1537.
8. Elias JJ, Soehnlen NT, Guseila LM, Cosgarea AJ. Dynamic tracking influenced by anatomy in patellar instability. *Knee*. 2016;23(3):450-455.
9. Farahmand F, Naghi Tahmasbi M, Amis A. The contribution of the medial retinaculum and quadriceps muscles to patellar lateral stability: an in-vitro study. *Knee*. 2004;11(2):89-94.

10. Fitzpatrick CK, Baldwin MA, Rullkoetter PJ. Computationally efficient finite element evaluation of natural patellofemoral mechanics. *J Biomech Eng*. 2010;132(12):121013.
11. Fitzpatrick CK, Steensen RN, Tumuluri A, Trinh T, Bentley J, Rullkoetter PJ. Computational analysis of factors contributing to patellar dislocation. *J Orthop Res*. 2016;34(3):444-453.
12. Grimm NL, Lazarides AL, Amendola A. Tibial tubercle osteotomies: a review of a treatment for recurrent patellar instability. *Curr Rev Musculoskelet Med*. 2018;11(2):266-271.
13. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng*. 1983;105(2):136-144.
14. Hamilton LD, Andreassen TE, Myers C, Shelburne KB, Clary C, Rullkoetter PJ. Supine leg press as an alternative to standing lunge in high-speed stereo radiography. *J Biomech*. 2022;138:111118.
15. Hevesi M, Heidenreich MJ, Camp CL, et al. The recurrent instability of the patella score: a statistically based model for prediction of long-term recurrence risk after first-time dislocation. *Arthroscopy*. 2019;35(2):537-543.
16. Laugharne E, Bali N, Purushothamdas S, Almallah F, Kundra R. Variability of measurement of patellofemoral indices with knee flexion and quadriceps contraction: an MRI-based anatomical study. *Knee Surg Relat Res*. 2016;28(4):297-301.
17. Ling DI, Brady JM, Arendt E, et al. Development of a multivariable model based on individual risk factors for recurrent lateral patellar dislocation. *J Bone Joint Surg Am*. 2021;103(7):586-592.
18. Petri M, Ettinger M, Stuebig T, et al. Current concepts for patellar dislocation. *Arch Trauma Res*. 2015;4(3):e29301.
19. Rezvanifar SC, Flesher BL, Jones KC, Elias JJ. Lateral patellar maltracking due to trochlear dysplasia: a computational study. *Knee*. 2019;26(6):1234-1242.
20. Rodriguez-Vila B, Sanchez-Gonzalez P, Oropesa I, Gomez EJ, Pierce DM. Automated hexahedral meshing of knee cartilage structures: application to data from the Osteoarthritis Initiative. *Comput Methods Biomech Biomed Engin*. 2017;20(14):1543-1553.
21. Smith TO, Donell S, Song F, Hing CB. Surgical versus non-surgical interventions for treating patellar dislocation. *Cochrane Database Syst Rev*. 2015;(2):CD008106.
22. Snow M. Tibial torsion and patellofemoral pain and instability in the adult population: current concept review. *Curr Rev Musculoskelet Med*. 2021;14(1):67-75.
23. Steensen RN, Bentley JC, Trinh TQ, Backes JR, Wiltfong RE. The prevalence and combined prevalences of anatomic factors associated with recurrent patellar dislocation: a magnetic resonance imaging study. *Am J Sports Med*. 2015;43(4):921-927.
24. Vogel LA, Pace JL. Trochleoplasty, medial patellofemoral ligament reconstruction, and open lateral lengthening for patellar instability in the setting of high-grade trochlear dysplasia. *Arthrosc Tech*. 2019;8(9):e961-e967.
25. Watts JC, Farrow LD, Elias JJ. Anatomical characteristics contributing to patellar dislocations following MPFL reconstruction: a dynamic simulation study. *J Biomech Eng*. 2023;145(4):041003.
26. Wierer G, Krabb N, Kaiser P, et al. The patellar instability probability calculator: a multivariate-based model to predict the individual risk of recurrent lateral patellar dislocation. *Am J Sports Med*. 2022;50(2):471-477.